

9184

NACA TN 2850

0065805



TECH LIBRARY KAFB, NM

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2850

STUDY OF PRESSURE EFFECTS ON VAPORIZATION RATE
OF DROPS IN GAS STREAMS

By Robert D. Ingebo

Lewis Flight Propulsion Laboratory
Cleveland, Ohio



Washington

January 1953

AFMCC
TECHNICAL LIBRARY
AFL 2811



0065805

18

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2850

STUDY OF PRESSURE EFFECTS ON VAPORIZATION RATE OF DROPS IN GAS STREAMS

By Robert D. Ingebo

SUMMARY

The determination of the rate of vaporization of a pure liquid from a spherical surface exposed to a gas stream of varying static pressure required the use of the heat-balance equation

$$\frac{dm}{d\theta} = \frac{hA}{H_v} \Delta t$$

where $dm/d\theta$ is the vaporization rate, h is the heat-transfer coefficient, A is the surface area of the drop, H_v is the latent heat of vaporization, and Δt is the difference between the gas temperature and the surface temperature of the drop. Sensible heat transferred by the liquid was negligible in comparison with latent-heat requirements.

Experimental data were obtained for four pure liquids tested over an air-stream static-pressure range of 450 to 1500 millimeters of mercury. Data were also obtained for methanol evaporating in constant-pressure streams of helium, argon, and carbon dioxide. The following semiempirical equation for predicting the evaporation rate of a drop was determined:

$$\frac{dm}{d\theta} = \frac{k_g \Delta t}{H_v} 2\pi d \left[1 + 1.29 \times 10^6 \left(\text{ReSc} \frac{gl}{c^2} \right)^{0.6} \left(\frac{k_g}{k_v} \right)^{0.5} \right]$$

where k_g and k_v are the thermal conductivities of the gas and the vapor, respectively, d is the drop diameter, Re and Sc are the Reynolds and Schmidt numbers, respectively, g is the acceleration due to gravity, l is the mean free path of the gas molecules, and c is the root-mean-square velocity of the gas molecules. This expression was obtained for the case of isolated drops and a very low value of approach-stream turbulence.

The evaporation-rate and the surface-temperature data obtained in this study show the heat-transfer coefficient to be independent of the static pressure of the system, and the effect of pressure on the vaporization rate to be determined directly by the effect of pressure on the surface temperature of the drop. An equation is also presented for calculating the Δt value for water at a static pressure of 450 to 1500 millimeters of mercury by use of the Δt value for 1-atmosphere pressure and a calculated correction term $\Delta t'$.

INTRODUCTION

Numerous investigations have been made to determine the effect of pressure on the vaporization rate of droplets in still air (references 1 to 4). However, at present, vaporization-rate data, which show the effect of pressure on the evaporation rate of drops in streams of air or other gases, are unavailable. Since combustion-chamber pressures of $1/3$ to 4 atmospheres may be encountered in the operation of jet engines, the effect of air-stream pressure on the vaporization rate of fuel droplets is of considerable importance in the study of combustible fuel vapor and air mixtures for jet combustors. Such mixtures are generally formed by the injection of fuel droplets at a point upstream of the combustion zone. Thus, the concentration of fuel vapor in the mixture entering the burning zone is determined by the vaporization rate of the droplets. In order to determine this rate in air streams of varying pressure, an investigation was made at the NACA Lewis laboratory in which a range of pressure conditions encountered in aircraft combustion systems was studied.

In reference 5, an equation is presented for simultaneous heat and mass transfer which showed the effect of molecular mass transfer and turbulent momentum transfer on the heat-transfer coefficient. This heat-balance equation may be used to predict the effect of drop diameter, fluid velocity, and temperature on vaporization rates. However, since the equation was determined for an air-stream pressure of 740 millimeters of mercury, it cannot be applied directly to vaporization at different air-stream pressures. The present report was therefore prepared as an extension of reference 5.

The vaporization rates of pure liquids in gas streams having static pressures of 450 to 1500 millimeters of mercury were determined for single constant-diameter drops simulated by wetted porous spheres. The experiments were conducted in air streams under the conditions of constant fluid velocity with varying pressure and mass-flow rates, constant pressure with varying velocity and mass-flow rates, and constant mass-flow rates with varying pressure and air-stream velocity. The mass-flow rate of air was varied over a Reynolds number range of 1360 to

3400 based on drop diameter, and surface-temperature data were obtained in all tests. A limited number of experiments were also made in streams of helium, argon, and carbon dioxide at constant pressure and varying mass-flow rates.

An analysis of the problem of simultaneous heat and mass transfer resulted in the development of a semiempirical equation which was found to correlate the experimental vaporization data. This expression was obtained for the case of single drops and small values of approach-stream turbulence.

SYMBOLS

The following symbols appear in this report:

| | |
|--------------|--|
| A | surface area of drop, sq cm |
| $b_{g,w}$ | molecular mass diffusivity evaluated at t_{av} , g/(cm)(sec) |
| \bar{c} | root-mean-square molecular velocity evaluated at t_s , cm/sec |
| \bar{c}' | root-mean-square molecular velocity of inert gas in presence of diffusing vapor, cm/sec |
| D_v | volumetric diffusion coefficient or diffusivity of vapor evaluated at t_{av} , sq cm/sec (reference 6) |
| d | drop diameter, cm |
| $dm/d\theta$ | vaporization rate, g/sec |
| Fr | Froude number, u^2/dg |
| f | proportionality constant |
| g | acceleration due to gravity, 980 cm/sec ² |
| H_v | latent heat of vaporization evaluated at t_s , g-cal/g |
| h | heat-transfer coefficient, g-cal/(sec)(sq cm)(°C) |
| K | mass-transfer coefficient, g/(sec)(sq cm) |
| k | thermal conductivity evaluated at t_{av} , g-cal/(sec)(sq cm)(°C/cm) |

| | |
|--------------|--|
| λ | mean free molecular path evaluated at t_s , cm |
| λ' | mean free molecular path of inert gas in presence of diffusing vapor, cm |
| M | molecular weight |
| m | quantity of material vaporized, g |
| n | number of molecules per unit volume |
| Nu | Nusselt group for heat transfer, $h\bar{d}/k$ |
| Nu' | Nusselt group for mass transfer, $K_d/b_{g,w}$ |
| P | static pressure, atm or mm Hg |
| p_b | log mean partial pressure of inert or nondiffusing gas, atm |
| p_v | difference between partial pressure of vapor at droplet surface and partial pressure of vapor in air stream, or driving potential, atm |
| R | universal gas constant, 8.31×10^7 ergs/($^{\circ}$ K)(mole) |
| Re | Reynolds number based on drop diameter with μ_{dp} and μ evaluated at t_g and t_{av} , respectively, μ_{dp}/μ |
| ReSc | new correlative group with μ_{dp} and $b_{g,w}$ evaluated at t_g and t_{av} , respectively, $\mu_{dp}/b_{g,w}$ |
| Sc | Schmidt group based on mass diffusivity and evaluated at t_{av} , $\mu/b_{g,w}$ |
| T | temperature, $^{\circ}$ K |
| t | temperature, $^{\circ}$ C |
| t_{av} | average film temperature, $\frac{1}{2} (t_g + t_s)$, $^{\circ}$ C |
| Δt | difference between air temperature and surface temperature of drop or driving potential, $t_g - t_s$, $^{\circ}$ C |
| $\Delta t'$ | temperature-difference correction term, $^{\circ}$ C |
| Δt^* | Δt value at 1 atm pressure, $^{\circ}$ C |

| | |
|----------|--|
| u | velocity of gas, cm/sec |
| V | molal volume, cu cm/g-mole |
| Z | rate of momentum transfer per unit area, $\text{g}/(\text{sec}^2)(\text{cm})$ |
| Z' | momentum transferred per collision per unit area, $\text{g}/(\text{sec})(\text{cm})$ |
| θ | vaporization time, sec |
| μ | gas viscosity, poises |
| ρ | gas or vapor density, g/cu cm |
| σ | diameter of gas molecule, cm |
| ϕ | prefix indicating function |

Subscripts:

| | |
|---|-------------------|
| a | air |
| f | film |
| g | gas |
| i | inertia force |
| j | gravity force |
| m | molecular scale |
| n | macroscopic scale |
| s | surface |
| t | temperature |
| v | vapor |
| w | water |

Superscript:

| | |
|---|--------------|
| n | any exponent |
|---|--------------|

APPARATUS AND PROCEDURE

The apparatus used in determining vaporization rates under varying air-stream-pressure conditions is shown in figure 1. Air was supplied from the central laboratory system at 50 pounds per square inch gage and 16-percent relative humidity. The air was metered by a rotameter and the temperature was controlled over a range of 22° to 93° C by an electric resistance heater. Air leaving the heater was passed through a calming chamber containing two sections of 200-mesh screen placed normal to the air stream and through a nozzle into the test section. The inlet ducting was designed to minimize approach-stream turbulence. Control valves placed upstream and downstream of the test section made it possible to adjust the air-stream pressure, velocity, and mass-flow rate to the desired values. The sphere was placed in the center of the test section and air temperatures were measured by a thermocouple mounted in the same horizontal plane as the sphere. Air-stream static pressures were measured from a pressure tap drilled in the wall of the test section at a point in the same horizontal plane as the sphere. Pressures investigated covered a range of 450 to 1500 millimeters of mercury.

The surface temperature of each liquid drop for the pressure and temperature ranges studied was obtained with a fine thermocouple junction of 40-gage iron-constantan wire flush with the surface of the sphere. A fine thermocouple junction was also placed in the center of the sphere to obtain the liquid-core temperature. By maintaining the liquid temperature near the surface temperature, the sensible-heat transferred by the liquid was negligible in comparison with the latent-heat of vaporization.

The vaporization unit (fig. 2) consisted of a syringe, a hypodermic needle, a cork sphere mounted on the end of the needle, a rubber stopper, and a stainless-steel tube. A screw-feed mechanism was required for injecting liquid into the sphere at air-stream pressures other than atmospheric pressure.

Vaporization rates were measured directly by weighing the unit on an analytical balance before and after each run. The technique consisted in:

- (1) Weighing the vaporization unit on an analytical balance
- (2) Inserting the stainless-steel-tube portion of the unit into the test section (fig. 1)
- (3) Starting the vaporization period by withdrawing the tube partially through the hole in the test section opposite the syringe, thus exposing the drop to the air stream for 2 minutes (fig. 2(b))

- (4) Ending the vaporization run by replacing the tube over the sphere and sealing with the rubber stopper (fig. 2(a))
- (5) Removing the unit from the test section, reweighing the unit, and obtaining the vaporization rate as the quantity of liquid evaporated per unit time

Vaporization-rate data for air streams were obtained for the following conditions: (a) constant fluid velocity with varying pressure and air-mass-flow rates, (b) constant pressure with varying velocity and air-mass-flow rates, and (c) constant air-mass-flow rates with varying pressure and fluid velocity.

A limited number of tests were made at constant pressure and varying mass-flow rates in which methanol was evaporated into streams of helium, argon, and carbon dioxide. In each case, the 1-inch pipe was disconnected from the outlet of the air heater (fig. 1) and connected by means of pipe fittings and a copper tube to a pressure regulator mounted on a cylinder containing the compressed gas. Thus, the gas was passed through the calming chamber and the test section; evaporation rates and surface-temperature data were obtained by the method described for air streams. The velocity of the gas stream near the surface of the sphere was measured with a pitot tube connected to a micromanometer.

RESULTS AND DISCUSSION

Effect of Pressure on Nusselt Number

The vaporization rate of a drop may be determined by either the mass-balance equation:

$$\frac{dm}{d\theta} = \pi d b_{g,w} p_v \frac{Nu'}{p_b} \quad (1)$$

or the heat-balance equation:

$$\frac{dm}{d\theta} = \frac{hA}{H_v} \Delta t = \pi d k_a \Delta t \frac{Nu}{H_v} \quad (2)$$

where p_v is the difference between the partial pressure of the vapor at the drop surface and in the air stream, Nu' is the Nusselt number for mass-transfer, and p_b the log mean partial pressure of the non-diffusing gas. Frössling (reference 7) presented the following expression for the mass-transfer Nusselt group for an air temperature of 20° C:

$$Nu' = 2 + 0.552 (Re)^{0.5} (Sc)^{0.33} \quad (2a)$$

However, in a more recent investigation (reference 5) it was found that this equation was not valid over an air temperature range of 30° to 500° C, and the following expression was presented for the heat-transfer Nusselt group:

$$Nu = \left(\frac{k_a}{k_v} \right)^{0.5} \left[2 + 0.303 (ReSc)^{0.6} \right] \quad (2b)$$

where the product of the Reynolds and Schmidt numbers $ReSc$ was defined as a single dimensionless number. The Prandtl number does not appear in this expression since it remained approximately constant throughout the tests, but the thermal-conductivity ratio k_a/k_v was included to make the expression directly applicable to an air-vapor film.

Equation (2b) was determined at an air pressure of 740 millimeters of mercury and therefore does not necessarily give the correct effect of pressure on the heat-transfer coefficient. It does, however, predict

$$Nu = \varphi(Re) = \varphi(P)$$

In order to test this prediction, evaporation rates and surface-temperature data were obtained for constant velocity air streams of 12.2 feet per second and a static-pressure range of 598 to 1494 millimeters of mercury. Data for these runs are given in table I and show that, although the pressure was varied by a factor of $2\frac{1}{2}$ the Nusselt number remained relatively constant. Thus, the pressure effect on the Nusselt group predicted from the Reynolds number does not appear to hold for this case of simultaneous heat and mass transfer.

The effect of air-mass-flow rate on the Nusselt number (for methanol) was investigated at different air-stream pressures, and data for these runs are recorded in table II and plotted in figure 3. From the two plots shown in figure 3, it is evident that the effect of pressure is not adequately expressed by the relation given in equation (2b).

Momentum-Transfer Groups

The analogy between momentum transfer and heat transfer is simply the concept that both heat and momentum are transferred when a molecule collides with a surface or another molecule. Thus, the heat transferred to a vaporizing drop by a molecular collision may be predicted from a knowledge of the momentum transferred in the collision. From the kinetic theory of gases, the momentum-transfer rate between molecules and a surface may be obtained in the following manner. The rate of momentum transfer resulting from gas molecules striking a surface may be given as:

$$Z_{i,m} \propto \rho \bar{c}^2$$

where $Z_{i,m}$ is the rate of molecular momentum transfer per unit area, ρ is the gas density, and \bar{c} is the root-mean-square velocity of the molecules. If this rate is divided by the rate of collisions at the surface \bar{c}/l , where l is the mean free molecular path,

$$Z'_{i,m} \propto \rho \bar{c} l \quad (3)$$

where $Z'_{i,m}$ is the momentum transferred per collision per unit area due to the force of inertia of single molecules.

If groups of molecules strike a surface at a velocity which is a function of the main-stream velocity of the gas u , the rate of momentum transfer per unit area may be written

$$Z_{i,n} \propto \rho u^2$$

The rate of collisions at a cylindrical or spherical surface is proportional to u/d since the film thickness is a function of the diameter d . For the force of inertia of groups of molecules, the momentum transferred per collision per unit area becomes

$$Z'_{i,n} \propto \rho u d \quad (4)$$

Consider the case of molecular groups transferring momentum due to the force of gravity, where film thickness is again a function of d . The rate of momentum transfer per unit area may be written

$$Z_{j,n} \propto \rho g d$$

where ρ is the average density of the gas. For the force of gravity acting on groups of molecules, the momentum transferred per collision per unit area is:

$$Z'_{j,n} \propto \rho \sqrt{g d} d \quad (5)$$

since the rate of collisions at the surface is proportional to $\sqrt{g d}/d$.

For the case of momentum transfer due to the force of gravity acting on single molecules, the rate of momentum transfer per unit area may be written

$$Z_{j,m} \propto \rho g l$$

where \bar{l} is the mean free molecular path. The rate of collisions at the surface is proportional to \sqrt{gl}/\bar{l} , and the momentum transferred per collision per unit area becomes

$$Z'_{j,m} \propto \rho \sqrt{gl} \bar{l}$$

for the force of gravity acting on single molecules.

The four cases of momentum transfer are summarized in the following table:

| Force | Scale | Rate of momentum transfer per unit area, Z (g/(sec ²)(cm)) | Collision rate at surface (collisions/sec) | Momentum transfer per collision per unit area, Z' (g/(sec)(cm)) |
|---------|-------------|---|---|--|
| Inertia | Molecular | $\rho \bar{c}^2$ | \bar{c}/\bar{l} | $\rho \bar{c} \bar{l}$ |
| Inertia | Macroscopic | ρu^2 | u/\bar{d} | $\rho u \bar{d}$ |
| Gravity | Molecular | $\rho g \bar{l}$ | \sqrt{gl}/\bar{l} | $\rho \sqrt{gl} \bar{l}$ |
| Gravity | Macroscopic | $\rho g \bar{d}$ | \sqrt{gd}/\bar{d} | $\rho \sqrt{gd} \bar{d}$ |

In a gas, there is a continuous transfer of momentum from the gas molecules to the containing surface. This may be measured as the pressure of the gas, and the momentum transferred per collision per unit area $\rho \bar{c} \bar{l}$ is proportional to the viscosity of the gas. If a quantity of gas is forced past the surface, momentum proportional to $\rho u \bar{d}$ is transferred to the surface. When a ratio of $\rho u \bar{d}$ to the momentum transferred without forced flow $\rho \bar{c} \bar{l}$ is used, the following Reynolds number relation can be obtained:

$$Re \propto \rho u \bar{d} / \rho \bar{c} \bar{l}$$

which is the ratio of macroscopic- to molecular-scale inertia forces. If heat is also transferred across the film to the surface because of a temperature difference $t_g - t_s$, then the Reynolds number may be evaluated at the gas temperature and another momentum-transfer ratio considered. Molecules in the film will transfer momentum proportional to $(\rho \bar{c} \bar{l})_{t,f}$ to the surface when heat is transferred across the film. Thus, the ratio of molecular-momentum transfer without heat transfer to that with heat transfer is $(\rho \bar{c} \bar{l})_{t,g} / (\rho \bar{c} \bar{l})_{t,f}$ where t,g indicates gas temperature and t,f average film temperature. This ratio should be included with the Reynolds number in the case of simultaneous heat and momentum transfer.

Consider the case of simultaneous momentum and mass transfer. Here the ratio $\rho u \bar{d} / \rho_v D_v$ appears to be important since groups of air

molecules transfer momentum equal to $\rho u d$ to the surface, and the diffusing-vapor molecules transfer momentum equal to $\rho_v D_v$ away from the surface. The momentum transfer per collision between air molecules and a liquid surface of unit area may be expressed as $(\rho \bar{c} l)_{t,s}$ provided that there is no diffusion of vapor from the liquid surface. However, with evaporation and diffusion occurring at the surface, the effective mean free path between air molecules will be greater than l since l' varies inversely with the concentration of air molecules. Also, the root-mean-square velocity of the air molecules may be less than \bar{c} since momentum is lost to the diffusing vapor. Thus, the collision frequency \bar{c}'/l' with mass transfer must be a function of the collision frequency \bar{c}/l obtained with no mass transfer, but it is considerably smaller than \bar{c}/l .

On a macroscopic scale, Froude (reference 8) has shown that if the collision frequency u/d is small the effect of gravity becomes very important and the Froude group $(\rho u d / \rho \sqrt{g d} d)^2$ is used to describe the momentum-transfer process. Thus, the molecular-scale group $\rho \sqrt{g l} l / \rho \bar{c} l$ which is analogous to the macroscopic-scale Froude group, may be considered important to the process when \bar{c}'/l' is small as in the case of momentum transfer to a vaporizing-liquid surface. The groups $ReSc$ and $(\rho \sqrt{g l} l)_{t,s} / (\rho \bar{c} l)_{t,s}$ are therefore important in the case of simultaneous momentum, mass, and heat transfer. This discussion is summarized in the following table:

| Process | Momentum-transfer groups |
|-----------------------------------|--|
| Momentum transfer | $\frac{(\rho u d)_{t,g}}{(\rho \bar{c} l)_{t,g}}$ |
| Momentum and heat transfer | $\frac{(\rho u d)_{t,g}}{(\rho \bar{c} l)_{t,g}}, \frac{(\rho \bar{c} l)_{t,g}}{(\rho \bar{c} l)_{t,f}}$ |
| Momentum, heat, and mass transfer | $\frac{(\rho u d)_{t,g}}{(\rho \bar{c} l)_{t,g}}, \frac{(\rho \bar{c} l)_{t,g}}{(\rho_v D_v)_{t,f}}, \frac{(\rho \sqrt{g l} l)_{t,s}}{(\rho \bar{c} l)_{t,s}}$ |

Application of Momentum-Transfer Groups to Heat and Mass Transfer

From the analogy between heat and momentum transfer, the ratio of macroscopic- to molecular-scale heat transfer or the Nusselt number hd/k would be expected to be a function of not only the groups given in equation 2(b), $ReSc$ and k_a/k_v , but also the molecular-scale momentum-transfer ratio at the liquid surface $(\rho \sqrt{g l} l)_{t,s} / (\rho \bar{c} l)_{t,s}$.

Thus, equation (2b) may be rewritten

$$hd/k_g = \phi [ReSc, k_g/k_v, (\rho \sqrt{gl} l)_{t,s}/(\rho \bar{c} l)_{t,s}] \quad (6)$$

The effect of $ReSc$ and k_g/k_v on the Nusselt group has already been shown (reference 5), and equation (6) may be written:

$$hd/k_g = f(k_g/k_v)^{0.5} (ReSc)^{0.6} (gl/\bar{c}^2)^n \quad (7)$$

where f is a proportionality constant and n an exponent.

The data in tables I and II indicate that the exponent n is equal to 0.6. In order to verify this, vaporization-rate data for four pure liquids were obtained in which the air-mass-flow rate was held constant at 9.33 grams per second and the air-stream pressure varied over a range of 450 to 1500 millimeters of mercury. These data, recorded in table III and plotted in figure 4, confirm the fact that the exponent n is equal to 0.6.

The dimensionless group gl/\bar{c}^2 may be written:

$$\frac{gl}{\bar{c}^2} = \frac{gM}{6RTmo^2} = 8.86 \times 10^{-7} \frac{M}{Tmo^2} \quad (8)$$

since $g = 980$ centimeters per second per second, and $R = 8.31 \times 10^7$ ergs per ($^{\circ}K$) (mole). The number of molecules in a unit volume of gas at any pressure P or temperature T may be written

$$n = \frac{6.02 \times 10^{23}}{22,400} \frac{P}{760} \frac{273}{T} = 0.966 \times 10^{19} \frac{P}{T}$$

where P is in millimeters of mercury and T is in $^{\circ}K$. By substituting this value for n in equation (8):

$$\frac{gl}{\bar{c}^2} = 9.18 \times 10^{-26} \frac{M}{P\sigma^2}$$

Thus, the dimensionless group gl/\bar{c}^2 is a function of pressure, molecular diameter, and molecular weight of the gas.

In the vaporization studies, air was used as the inert heat-transfer medium. The best available values of collision diameter were used here, but they must be regarded as approximate. Since nitrogen and oxygen have collision diameters of approximately 3.77×10^{-8} and

3.62×10^{-8} centimeters, respectively, (reference 9), the diameter of an air molecule may be taken as approximately 3.7×10^{-8} centimeters. Thus, for air

$$\frac{M}{\sigma^2} = \frac{29}{(3.7 \times 10^{-8})^2} = 2.12 \times 10^{16}$$

In order to test the applicability of the group gl/\bar{c}^2 to gas streams other than air, vaporization tests were performed in which methanol was evaporated from the surface of a porous sphere into constant-pressure streams of argon, helium, and carbon dioxide. By this means, it was possible to test the effect of molecular properties separate from the pressure effect given in the group gl/\bar{c}^2 . Prandtl numbers and values of M/σ^2 for these gases and air are shown in the following table:

| Gas | σ (cm) (references 9 and 10) | Molecular weight | M/σ^2 | Prandtl number |
|----------------|---|---------------------|-----------------------|-------------------|
| Air | 3.70×10^{-8} | 29 | 2.12×10^{16} | 0.74 |
| Helium | 2.20 | 4 | 0.83 | .69 |
| Argon | 2.86 | 40 | 4.88 | .68 |
| Carbon dioxide | 3.40 | 44 | 3.81 | .80 |

By obtaining evaporation rates in gases other than air, it was also possible to vary the thermal-conductivity ratio k_g/k_v by a factor of approximately 10. Data for these tests are recorded in table IV and plotted in figure 5. Data given in table III are also plotted in figure 5, and a straight line having a slope of 0.5, which was obtained in reference 5, is drawn in the figure for comparison. Thus, by use of the molecular-scale momentum-transfer group gl/\bar{c}^2 , it was possible to correlate vaporization-rate data for methanol evaporating in streams of air, helium, argon, and carbon dioxide with the thermal-conductivity ratio for a given vapor-gas system.

Equation (2b) predicts that the Nusselt number for a still gas may be expressed as:

$$Nu = 2(k_g/k_v)^{0.5}$$

The data used in deriving equation (2b) (reference 5) may be replotted as shown in figure 6. The equation for this plot is

$$Nu = 2 + 0.303 (ReSc)^{0.6} (k_g/k_v)^{0.5} \quad (2c)$$

This equation shows the Nusselt number for still air to be independent of the thermal-conductivity ratio.

Thus, the data in reference 5 cannot be used to determine whether equation (2b) or (2c) is the correct form since the Reynolds numbers were relatively high. However, in the present investigation, evaporation data for the helium-methanol system extended the range of the data to include high values of the thermal-conductivity ratio at low Reynolds numbers, and definitely show that equation (2c) is the correct form. The data of tables III and IV, plotted in figure 7, yield the following expression for Nusselt number

$$\frac{hd}{k_g} = 2 + 2.58 \times 10^6 \left(\frac{d_{up}}{b_{g,w}} \frac{gl}{c^2} \right)^{0.6} \left(\frac{k_g}{k_v} \right)^{0.5} \quad (9)$$

Data by Frössling (reference 7) are included in this plot to extend the correlation to low $ReSc$ values. In reference 5, the value of $(gl/\bar{c}^2)^{0.6}$ is 1.125×10^{-7} . Thus, the proportionality constant f is 0.303 divided by 1.125×10^{-7} or 2.69×10^6 which is approximately 5 percent higher than the value obtained for f in this investigation.

If the terms in equation (9) for the Nusselt number are substituted in equation (2), the following vaporization-rate equation is obtained:

$$\frac{dm}{d\theta} = \frac{k_g \Delta t}{H_v} 2\pi d \left[1 + 1.29 \times 10^6 \left(ReSc \frac{gl}{c^2} \right)^{0.6} \left(\frac{k_g}{k_v} \right)^{0.5} \right] \quad (10)$$

where Δt is the difference between the gas and the surface temperature in $^{\circ}C$, and H_v the latent-heat of vaporization in gram-calories per gram. In this equation, the group $(ReSc \, gl/\bar{c}^2)$ is independent of pressure, and the effect of gas-stream pressure on the evaporation rate may be determined directly from the effect of pressure on the driving potential Δt .

In order to test the applicability of equation (10) to the case of vaporization of a fuel drop in a more humid air stream, a series of tests was performed in which *n*-octane was vaporized in an air stream having a relative humidity of 48 percent. The vaporization rate and the surface temperature of the droplet were within 2 percent of the values previously determined in an air stream having a relative humidity of 16 percent. From this study, the relative humidity of the air stream appeared to have very little effect on the vaporization rate of the fuel droplet; this agrees with the fact that the effect of water vapor on the value of M/σ^2 for the gas stream was small.

Effect of Pressure on Driving Potential

Psychrometric data for water, over a pressure range of 147 to 1523 millimeters of mercury are shown in figure 8. Values of $\Delta t'$ were obtained from figure 8 at constant air temperatures above 100°C by use of the relation $\Delta t' = 0$ at a total pressure of 1 atmosphere. These changes in Δt with pressure at constant temperature may be plotted against the pressure in atmospheres as shown in figure 9. The equation of the straight line in the figure is

$$\Delta t' = -33 \log P \quad (11)$$

where $\Delta t'$ is the temperature-difference correction in $^{\circ}\text{C}$ and P is static pressure in atmospheres. Thus, the Δt values for water at any pressure from 0.2 to 2.0 atmospheres may be determined directly from the expression

$$\Delta t = \Delta t^* - 33 \log P \quad (12)$$

where Δt^* is the Δt value at 1 atmosphere. It will be necessary to relate Δt and P for other liquids if equation (10) is to be used for direct calculation of evaporation rate.

Application of Group gl/\bar{c}^2 to Data on Heat Transfer Inside

Wetted-Wall Columns

Vaporization-rate data are reported by Gilliland and Sherwood (reference 11) for the evaporation of liquids from the inside of wetted-wall cylinders into varying pressure and mass-flow-rate air streams. The mass-transfer Nusselt number Nu' was found to be a function of only the Reynolds and the Schmidt numbers provided that the air-stream pressure is assumed to have little effect on the liquid-surface temperature or driving potential p_v (see equation (1)). In their study it would have been very difficult to obtain surface-temperature data. However, in the present investigation, these data were obtained and may be applied to Gilliland and Sherwood's data as shown in table V. In this table, a portion of their data on vaporization of water (table I of reference 9) has been selected for examination at air-stream Reynolds numbers of approximately 2150. Estimated Δt values obtained from the experimental data in figure 9 are included in table V as are calculated values of the dimensionless groups Nu' and gl/\bar{c}^2 , which are also plotted in figure 10.

In the case of evaporation from inside wetted-wall columns, the usefulness of the group gl/\bar{c}^2 in explaining the effect of pressure

on simultaneous heat and mass transfer is readily apparent from figure 10 when both the Reynolds and Schmidt numbers are constant. Thus, their data and the data in this study show the Nusselt number for simultaneous heat and mass transfer to be a function of the three groups gl/\bar{c}^2 , Re , and Sc . If the Gilliland and Sherwood data were extended to air temperatures of 90° C or above, using water, the effect of pressure on the Reynolds number would be much greater than the effect of pressure on the driving potential Δt , as shown in figure 8, and in this case the importance of using the dimensionless group gl/\bar{c}^2 would be shown more clearly.

CONCLUSIONS

The experimental data show that the effect of gas-stream pressure on the evaporation rate of a pure liquid drop may be described by the equation

$$\frac{dm}{d\theta} = \frac{k_g \Delta t}{H_v} 2\pi d \left[1 + 1.29 \times 10^6 \left(Re Sc \frac{gl}{\bar{c}^2} \right)^{0.6} \left(\frac{k_g}{k_v} \right)^{0.5} \right]$$

where $dm/d\theta$ is the vaporization rate; k_g is the thermal conductivity of the gas, t is the difference between the air temperature and the surface temperature of the drop, H_v is the latent heat of vaporization, d is the drop diameter, Re is the Reynolds number, Sc is the Schmidt number, g is the acceleration due to gravity, \bar{c} is the mean free molecular path, \bar{c} is the root-mean-square molecular velocity, and k_v is the thermal conductivity of the vapor; $ReSc$ is a new correlative group, and gl/\bar{c}^2 is the molecular-scale ratio of gravitational to inertial forces. Thus, the Nusselt number is independent of the static pressure, and the effect of gas-stream pressure on the vaporization rate may be determined directly from the effect of pressure on the driving force Δt . The preceding relation was evolved for the case of an isolated drop and a very low value of approach-stream turbulence.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 10, 1952

APPENDIX - CALCULATION OF DIMENSIONLESS GROUPS

Nusselt group for n-octane (table I). -

| | |
|---|-----------------------|
| Sphere diameter, d, cm | 0.724 |
| Air temperature, t_a , °C | 28° |
| Surface temperature, t_s , °C | 18 |
| Temperature difference, $t_a - t_s$, °C | 10 |
| Average film temperature, t_{av} , °C | 23 |
| Vaporization rate, $dm/d\theta$, g/sec | 5.50×10^{-4} |
| Latent heat of vaporization at t_s , H_v , g-cal/g | 89 |
| Thermal conductivity of air at t_f , k_a , g-cal/(sec)(sq cm)(°C/cm) | 5.95×10^{-5} |

The Nusselt number may be expressed as

$$Nu = \frac{dm/d\theta H_v}{\pi d k_a \Delta t}$$

Thus

$$Nu = \frac{(5.50 \times 10^{-4})(89)}{(3.14)(0.724)(5.95 \times 10^{-5})(10)} = 36.2$$

Reynolds group for n-octane (table I). -

| | |
|---|------------------------|
| Mass-air-flow rate, lb/hr | 60 |
| Sphere diameter, d, cm | 0.724 |
| Area of duct, sq cm | 21.2 |
| Average film temperature, t_{av} , °C | 23 |
| Viscosity of air at t_f , μ_a , poise | 1.825×10^{-4} |

The mass-flow rate per unit area u_p may be calculated as follows:

$$u_p = \frac{(60)(454 \text{ g/lb})}{(3600 \text{ sec/hr})(21.2)} = 0.357 \text{ g/(sec)(sq cm)}$$

Thus, the Reynolds number is

$$Re = \frac{d u_p}{\mu_a} = \frac{(0.724)(0.357)}{(1.825 \times 10^{-4})} = 1413$$

Schmidt group for n-octane, (table III). -

| | |
|---|------------------------|
| Average film temperature, t_{av} , °C | 25 |
| Viscosity of air at t_f , μ_a , poise | 1.835×10^{-4} |

The molecular mass diffusivity $b_{g,w}$ may be calculated from the Gilliland expression (reference 6) as follows:

$$b_{g,w} = \frac{PM_v}{RT} D_v = \frac{PM_v}{RT} (0.0043) \frac{T^{3/2}}{P} \frac{(1/M_a + 1/M_v)^{0.5}}{(v_a^{1/3} + v_v^{1/3})^2}$$

$$b_{g,w} = \frac{114}{82} (0.0043) (298)^{0.5} (0.00269) = 2.77 \times 10^{-4} \text{ g/(cm)(sec)}$$

Thus, the Schmidt number is

$$Sc = \frac{\mu_a}{b_{g,w}} = \frac{1.835 \times 10^{-4}}{2.77 \times 10^{-4}} = 0.662$$

Molecular-scale momentum-transfer group gl/\bar{c} . -

The mean free molecular path l may be expressed as

$$l = 1/\sqrt{2}n\sigma^2$$

where the number of molecules per unit volume n is 2.7×10^{19} at a temperature of 0° C and a pressure of 1 atmosphere and the diameter of air molecule σ is 3.7×10^{-8} cm.

Thus

$$l = 6.11 \times 10^{-6} \text{ cm}$$

The root-mean-square molecular velocity \bar{c} may be expressed as

$$\bar{c} = \sqrt{\frac{3RT}{M}}$$

Thus

$$\frac{c^2}{c} = \frac{(3)(8.31 \times 10^7)(273)}{(29)} = 2.35 \times 10^9 \text{ (cm/sec)}^2$$

Since g is 980 centimeters per second per second,


$$\frac{gl}{c^2} = \frac{(980)(6.11 \times 10^{-6})}{(2.35 \times 10^9)} = 2.55 \times 10^{-12}$$

REFERENCES

1. Bradley, R. S., Evans, M. G., and Whytlaw-Gray, R. W.: The Rate of Evaporation of Droplets. I - Evaporation and Diffusion Coefficients, and Vapour Pressures of Dibutyl Phthalate and Butyl Stearate. Proc. Roy. Soc. (London), vol. 186, no. A 1006, ser. A, Sept. 1946, pp. 368-390.
2. Birks, J., and Bradley, R. S.: The Rate of Evaporation of Droplets. II - The Influence of Changes of Temperature and of the Surrounding Gas on the Rate of Evaporation of Drops of Di-n-butyl Phthalate. Proc. Roy. Soc. (London), vol. 198, no. A 1053, ser. A, Aug. 1949, pp. 226-239.
3. Bradley, R. S., and Shellard, A. D.: The Rate of Evaporation of Droplets. III - Vapour Pressures and Rates of Evaporation of Straight-Chain Paraffin Hydrocarbons. Proc. Roy. Soc. (London), vol. 198, no. A 1053, ser. A, Aug. 1949, pp. 239-251.
4. Bradley, R. S.: Rates of Evaporation. IV - The Rate of Evaporation and Vapour Pressure of Rhombic Sulfur. Proc. Roy. Soc. (London), vol. 205, no. A 1083, ser. A, March 1951, pp. 553-563.
5. Ingebo, Robert D.: Vaporization Rates and Heat-Transfer Coefficients for Pure Liquid Drops. NACA TN 2368, 1951.
6. Gilliland, E. R.: Diffusion Coefficients in Gaseous Systems. Ind. and Eng. Chem., vol. 26, no. 6, June 1934, pp. 681-685.
7. Frössling, Nils: Über die Verdunstung fallender Tropfen. Gerl. Beitr. Geophys., Bd. 52, Heft 1/2, 1938, pp. 170-216.
8. Merrifield, C. W.: The Experiments Recently Proposed on the Resistance of Ships. Trans. Inst. Naval Arch. (London), vol. XI, 1870, pp. 80-82; discussion, pp. 82-93.
9. Glasstone, Samuel: Textbook of Physical Chemistry. D. Van Norstrand Co., Inc., 2nd ed., 1946.

10. Hodgman, Charles D., and Holmes, Harry N.: Handbook of Chemistry and Physics. Chem. Rubber Pub. Co., (Cleveland), 25th ed., 1941, p. 1759.
11. Gilliland, E. R. and Sherwood, R. K.: Diffusion of Vapors into Air Streams. Ind. and Eng. Chem., vol. 26, no. 5, May 1934, pp. 516-523.
12. Lange, Norbert Adolph: Handbook of Chemistry. Handbook Publishers, Inc., 6th ed., 1946.


TABLE I - VAPORIZATION FROM 0.724-CENTIMETER-DIAMETER SPHERE IN
AIR STREAM AT TEMPERATURE OF 28° C AND VELOCITY
OF 12.2 FEET PER SECOND



| Air-flow rate (g/sec) | P (mm Hg) | Δt (°C) | $\frac{dm}{d\theta}$ (g/sec) | μ_a , evaluated at t_{av} (poises) (a) | Re | H_v (g-cal/g) (a) | k_a $\left(\frac{\text{g-cal}}{(\text{sec})(\text{sq cm})(^\circ\text{C/cm})} \right)$ (a) | Nu |
|------------------------------|--------------|--------------------|---------------------------------|---|------|---------------------------|---|------|
| <u>n</u> -Octane and air | | | | | | | | |
| 7.57 | 598 | 10.0 | 5.50×10^{-4} | 1.825×10^{-4} | 1413 | 88.9 | 5.95×10^{-5} | 36.2 |
| 9.47 | 747 | 8.3 | 4.53 | 1.830 | 1762 | 88.5 | 5.96 | 35.6 |
| 11.83 | 934 | 6.7 | 3.65 | 1.832 | 2200 | 88.4 | 5.98 | 35.5 |
| Carbon tetrachloride and air | | | | | | | | |
| 7.57 | 598 | 33.6 | 30.8×10^{-4} | 1.772×10^{-4} | 1452 | 52.5 | 5.76×10^{-5} | 36.7 |
| 9.47 | 747 | 30.1 | 27.5 | 1.775 | 1818 | 52.3 | 5.79 | 36.3 |
| 11.83 | 934 | 27.0 | 24.6 | 1.780 | 2262 | 52.1 | 5.80 | 35.9 |
| 14.20 | 1121 | 25.4 | 23.3 | 1.785 | 2710 | 52.0 | 5.82 | 36.4 |
| 16.58 | 1307 | 24.0 | 22.0 | 1.790 | 3150 | 51.9 | 5.84 | 35.6 |
| 18.93 | 1495 | 22.0 | 20.8 | 1.795 | 3600 | 51.7 | 5.86 | 36.7 |

^aValues from reference 12.

TABLE II - VAPORIZATION OF METHANOL FROM 0.71-CENTIMETER-DIAMETER
SPHERE IN AIR STREAM AT TEMPERATURE OF 28° C^a



| Air-mass- flow rate (g/sec) | P (mm Hg) | Δt (°C) | $\frac{dm}{d\theta}$ (g/sec) | Re | Nu | $\frac{Nu}{(k_a/k_v)^{0.5}}$ | ReSc |
|---|--------------|--------------------|---------------------------------|-------|------|------------------------------|-------|
| $\mu_f = 1.775 \times 10^{-4}$ poises; $H_v = 285$ g-cal/g; $k_a = 5.79 \times 10^{-5}$ and $k_v = 3.57 \times 10^{-5}$ g-cal/(sec)(sq cm)(°C/cm); and $b_{g,w} = 1.765 \times 10^{-4}$ g/cm sec. | | | | | | | |
| 20.55 | 740 | 30 | 8.25×10^{-4} | 3,870 | 60.7 | 47.7 | 3,892 |
| 16.65 | 740 | 30 | 7.22 | 3,136 | 53.1 | 41.7 | 3,154 |
| 13.00 | 740 | 30 | 6.42 | 2,448 | 47.2 | 37.1 | 2,462 |
| 9.33 | 740 | 30 | 5.25 | 1,757 | 38.6 | 30.3 | 1,767 |
| $\mu_v = 1.760 \times 10^{-4}$ poises; $H_v = 286$ g-cal/g; $k_a = 5.74 \times 10^{-5}$ and $k_v = 3.54 \times 10^{-5}$ g-cal/(sec)(sq cm)(°C/cm); and $b_{g,w} = 1.758 \times 10^{-4}$ g/cm sec. | | | | | | | |
| 9.33 | 506 | 36 | 7.52×10^{-4} | 1,772 | 46.6 | 36.7 | 1,775 |
| 8.58 | 506 | 36 | 7.08 | 1,630 | 43.8 | 34.5 | 1,634 |
| 7.82 | 506 | 36 | 7.02 | 1,485 | 43.6 | 34.3 | 1,488 |
| 10.10 | 506 | 36 | 7.57 | 1,920 | 47.0 | 36.9 | 1,923 |
| 10.72 | 506 | 36 | 8.07 | 2,100 | 50.1 | 39.4 | 2,104 |
| 13.00 | 506 | 36 | 9.40 | 2,470 | 58.3 | 45.7 | 2,475 |
| 16.65 | 506 | 36 | 10.15 | 3,180 | 63.0 | 49.5 | 3,185 |
| 20.55 | 506 | 36 | 11.98 | 3,900 | 74.4 | 58.4 | 3,905 |
| 29.20 | 506 | 36 | 14.28 | 5,550 | 88.5 | 69.5 | 5,557 |

^aValues for μ_f , H_v , k_a , and k_v from reference 12.

TABLE III - VAPORIZATION FROM SPHERES IN AIR STREAM AT A MASS-FLOW RATE OF 9.33 GRAMS PER SECOND^a

| P (mm Hg) | Δt (°C) | $dm/d\theta$ (g/sec) | Nu | l (cm) | $\frac{gl}{c^2}$ | $(ReSc \ gl/c^2)^{0.6}$ | $(ReSc \ gl/c^2)^{0.6} (k_a/k_v)^{0.5}$ |
|--|--------------------|-------------------------|------|-----------------------|------------------------|-------------------------|---|
| n-Octane and air; $t_a = 29.4^\circ \text{C}$; sphere diam. = 0.78 cm; $\mu_f = 1.835 \times 10^{-4}$ poises; $Re = 1875$; $\bar{c}^2 = 2.53 \times 10^9 \text{ (cm/sec)}^2$; $Sc = 0.662$; $H_v = 88.5 \text{ g-cal/g}$; and $k_a = 6.06 \times 10^{-5}$ and $k_v = 2.20 \times 10^{-5} \text{ g-cal/(sec)(sq cm)(}^\circ\text{C/cm)}$. | | | | | | | |
| 795 | 8.6 | 5.06×10^{-4} | 35.5 | 6.32×10^{-6} | 2.45×10^{-12} | 7.75×10^{-6} | 12.80×10^{-6} |
| 795 | 8.6 | 5.01 | 36.2 | 6.32 | 2.45 | 7.75 | 12.80 |
| 1016 | 6.6 | 3.34 | 30.6 | 4.94 | 1.92 | 6.70 | 11.05 |
| 1295 | 5.5 | 2.25 | 24.7 | 3.89 | 1.55 | 5.90 | 9.73 |
| 1511 | 4.9 | 1.86 | 22.9 | 3.34 | 1.29 | 5.27 | 8.70 |
| 892 | 7.2 | 3.77 | 31.6 | 5.64 | 2.18 | 7.25 | 11.95 |
| 1143 | 6.1 | 2.71 | 26.8 | 4.38 | 1.70 | 6.24 | 10.30 |
| 1016 | 6.6 | 3.13 | 28.7 | 4.94 | 1.92 | 6.70 | 11.05 |
| 638 | 10.5 | 6.83 | 39.2 | 7.86 | 3.06 | 8.88 | 14.63 |
| 495 | 11.8 | 8.71 | 44.6 | 10.15 | 3.95 | 10.33 | 17.03 |
| 717 | 10.0 | 6.16 | 37.2 | 7.02 | 2.70 | 8.25 | 13.60 |
| Benzene and air; $t_a = 27.8^\circ \text{C}$; sphere diam. = 0.78 cm; $\mu_f = 1.787 \times 10^{-4}$ poises; $Re = 1925$; $\bar{c}^2 = 2.48 \times 10^9 \text{ (cm/sec)}^2$; $Sc = 0.750$; $H_v = 106.5 \text{ g-cal/g}$; and $k_a = 5.82 \times 10^{-5}$ and $k_v = 2.35 \times 10^{-5} \text{ g-cal/(sec)(sq cm)(}^\circ\text{C/cm)}$. | | | | | | | |
| 798 | 24.4 | 12.4×10^{-4} | 38.0 | 6.17×10^{-6} | 2.44×10^{-12} | 8.47×10^{-6} | 13.33×10^{-6} |
| 798 | 24.4 | 12.9 | 39.5 | 6.17 | 2.44 | 8.47 | 13.33 |
| 798 | 24.4 | 12.5 | 38.2 | 6.17 | 2.44 | 8.47 | 13.33 |
| 892 | 23.2 | 10.8 | 34.7 | 5.53 | 2.19 | 7.94 | 12.50 |
| 892 | 23.2 | 11.0 | 35.4 | 5.53 | 2.19 | 7.94 | 12.50 |
| 495 | 30.0 | 20.3 | 50.5 | 9.95 | 3.95 | 11.33 | 17.83 |
| 1310 | 19.3 | 7.5 | 29.0 | 3.77 | 1.49 | 6.32 | 9.95 |

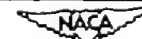
^aValues of μ_f , H_v , k_a , and k_v from reference 12.

TABLE III - Concluded. VAPORIZATION FROM SPHERES IN AIR STREAM AT A MASS-FLOW RATE
OF 9.33 GRAMS PER SECOND^a

| P (mm Hg) | Δt (°C) | $\frac{dm}{d\theta}$ (g/sec) | Nu | l (cm) | gl/\bar{c}^2 | $(ReSc \ gl/\bar{c}^2)^{0.6}$ | $(ReSc \ gl/\bar{c}^2)^{0.6} \times (k_a/k_v)^{0.5}$ |
|--|--------------------|---------------------------------|------|-----------------------|------------------------|-------------------------------|--|
| Acetone and air; $t_a = 27.8^\circ \text{C}$; sphere diam. = 0.64 cm; $\mu_f = 1.760 \times 10^{-4}$ poises; $Re = 1602$; $\bar{c}^2 = 2.28 \times 10^9 \text{ (cm/sec)}^2$; $Sc = 0.83$; $H_v = 135.5 \text{ g-cal/g}$; and $k_a = 5.74 \times 10^{-5}$ and $k_v = 2.43 \times 10^{-5} \text{ g-cal/(sec)(sq cm)(}^\circ\text{C/cm)}$. | | | | | | | |
| 1021 | 34.0 | 8.8×10^{-4} | 30.4 | 4.44×10^{-6} | 1.92×10^{-12} | 6.98×10^{-6} | 10.72×10^{-6} |
| 1036 | 33.8 | 8.6 | 29.9 | 4.38 | 1.89 | 6.90 | 10.50 |
| 742 | 37.1 | 10.9 | 34.5 | 6.12 | 2.63 | 8.44 | 12.98 |
| 742 | 37.1 | 11.3 | 35.7 | 6.12 | 2.63 | 8.44 | 12.98 |
| 1196 | 32.4 | 7.6 | 27.5 | 3.80 | 1.63 | 6.34 | 9.75 |
| 1196 | 32.4 | 7.2 | 26.1 | 3.80 | 1.63 | 6.34 | 9.75 |
| 890 | 35.4 | 9.8 | 32.5 | 5.12 | 2.19 | 7.56 | 11.62 |
| 890 | 35.4 | 9.5 | 31.5 | 5.12 | 2.19 | 7.56 | 11.62 |
| 890 | 35.4 | 10.0 | 32.2 | 5.12 | 2.19 | 7.56 | 11.62 |
| 648 | 38.4 | 12.8 | 39.1 | 7.02 | 3.01 | 9.15 | 14.06 |
| 446 | 41.6 | 18.5 | 52.2 | 10.20 | 4.39 | 11.50 | 17.70 |
| 470 | 41.1 | 17.0 | 48.5 | 9.68 | 4.16 | 11.05 | 17.00 |
| Acetone and air; $t_a = 93.0^\circ \text{C}$; sphere diam. = 0.688 cm; $\mu_f = 1.945 \times 10^{-4}$ poises; $Re = 1551$; $\bar{c}^2 = 2.38 \times 10^9 \text{ (cm/sec)}^2$; $Sc = 0.90$; $H_v = 134.2 \text{ g-cal/g}$; and $k_a = 6.37 \times 10^{-5}$ and $k_v = 3.00 \times 10^{-5} \text{ g-cal/(sec)(sq cm)(}^\circ\text{C/cm)}$. | | | | | | | |
| 798 | 89.0 | 29.3×10^{-4} | 32.1 | 5.94×10^{-6} | 2.44×10^{-12} | 8.32×10^{-6} | 12.15×10^{-6} |
| 798 | 89.0 | 28.5 | 31.2 | 5.94 | 2.44 | 8.32 | 12.15 |
| 1153 | 84.3 | 22.8 | 26.6 | 4.08 | 1.68 | 6.65 | 9.70 |
| 592 | 91.6 | 35.2 | 37.5 | 7.98 | 3.29 | 9.90 | 14.42 |
| 452 | 93.5 | 43.6 | 45.5 | 10.46 | 4.32 | 11.67 | 17.00 |
| 495 | 93.0 | 40.8 | 42.8 | 9.55 | 3.95 | 11.10 | 16.18 |
| Methanol and air; $t_a = 22.0^\circ \text{C}$; sphere diam. = 0.688 cm; $\mu_f = 1.752 \times 10^{-4}$ poises; $Re = 1732$; $\bar{c}^2 = 2.30 \times 10^9 \text{ (cm/sec)}^2$; $Sc = 1.00$; $H_v = 285 \text{ g-cal/g}$; and $k_a = 5.71 \times 10^{-5}$ and $k_v = 3.50 \times 10^{-5} \text{ g-cal/(sec)(sq cm)(}^\circ\text{C/cm)}$. | | | | | | | |
| 1321 | 22.8 | 2.33×10^{-4} | 23.7 | 3.48×10^{-6} | 1.48×10^{-12} | 7.00×10^{-6} | 8.94×10^{-6} |
| 792 | 28.9 | 4.32 | 34.6 | 5.78 | 2.47 | 9.52 | 12.17 |
| 1011 | 25.8 | 3.23 | 29.0 | 4.53 | 1.93 | 8.20 | 10.48 |
| 1179 | 24.5 | 2.74 | 25.9 | 3.89 | 1.66 | 7.48 | 9.55 |
| 892 | 27.5 | 3.75 | 31.5 | 5.12 | 2.18 | 8.83 | 11.28 |
| 508 | 32.0 | 3.61 | 44.8 | 9.00 | 3.84 | 12.40 | 15.82 |

^aValues of μ_f , H_v , k_a , and k_v from reference 12.

TABLE IV - VAPORIZATION OF METHANOL FROM 0.71-CENTIMETER-DIAMETER SPHERE IN GAS STREAMS OF

VARYING MASS-FLOW RATE^a

| P (mm Hg) | Δt (°C) | $\frac{dm}{d\theta}$ (g/sec) | u (cm/sec) | Nu | Re | ReSc | gl/\bar{c}^2 | $(ReSc \ gl/\bar{c}^2)^{0.6}$ | $(ReSc \ gl/\bar{c}^2)^{0.6} (k_g/k_v)^{0.5}$ |
|---|--------------------|---------------------------------|---------------|-------|------|-------|-------------------------|-------------------------------|---|
| Methanol and helium; $t_g = 26^\circ \text{C}$; $\mu_g = 1.876 \times 10^{-4}$ poises; $H_v = 285$ g-cal/g; $k_g = 33.6 \times 10^{-5}$ and $k_v = 3.40 \times 10^{-5}$ g-cal/(sec)(sq cm)(°C/cm); and $b_{g,w} = 3.70 \times 10^{-4}$ g/(cm)(sec). | | | | | | | | | |
| 740 | 28 | 10.22×10^{-4} | 556 | 13.88 | 340 | 172.5 | 1.024×10^{-12} | 1.418×10^{-6} | 4.5×10^{-6} |
| 740 | 28 | 10.10 | 556 | 13.72 | 340 | 172.5 | 1.024 | 1.418 | 4.5 |
| 740 | 28 | 12.23 | 766 | 16.62 | 468 | 237.0 | 1.024 | 1.702 | 5.4 |
| 740 | 28 | 12.53 | 766 | 17.05 | 468 | 237.0 | 1.024 | 1.702 | 5.4 |
| Methanol and Argon; $t_g = 15.5^\circ \text{C}$; $\mu_g = 2.18 \times 10^{-4}$ poises; $H_v = 286$ g-cal/g; $k_g = 3.90 \times 10^{-5}$ and $k_v = 3.36 \times 10^{-5}$ g-cal/(sec)(sq cm)(°C/cm); and $b_{g,w} = 1.61 \times 10^{-4}$ g/(cm)(sec). | | | | | | | | | |
| 740 | 26.5 | 3.97×10^{-4} | 231 | 49.3 | 1335 | 1810 | 6.05×10^{-12} | 16.7×10^{-6} | 18.0×10^{-6} |
| 740 | 26.5 | 3.98 | 231 | 49.5 | 1335 | 1810 | 6.05 | 16.7 | 18.0 |
| 740 | 26.5 | 4.35 | 313 | 54.1 | 1935 | 2450 | 6.05 | 20.1 | 21.6 |
| 740 | 26.5 | 4.33 | 313 | 53.9 | 1935 | 2450 | 6.05 | 20.1 | 21.6 |
| Methanol and CO ₂ ; $t_g = 13.0^\circ \text{C}$; $\mu_g = 1.44 \times 10^{-4}$ poises; $H_v = 286$ g-cal/g; $k_g = 3.39 \times 10^{-5}$ and $k_v = 3.36 \times 10^{-5}$ g-cal/(sec)(sq cm)(°C/cm); and $b_{g,w} = 1.60 \times 10^{-4}$ g/(cm)(sec). | | | | | | | | | |
| 740 | 24.0 | 3.73×10^{-4} | 426 | 58.8 | 3870 | 3480 | 4.72×10^{-12} | 21.3×10^{-6} | 21.4×10^{-6} |
| 740 | 24.0 | 2.56 | 240 | 41.0 | 2180 | 1965 | 4.72 | 15.2 | 15.3 |
| 740 | 24.0 | 2.56 | 240 | 40.4 | 2180 | 1965 | 4.72 | 15.2 | 15.3 |

^aValues for μ_g , H_v , k_g , and k_v from reference 12.

TABLE V - VAPORIZATION OF WATER FROM INSIDE WETTED-WALL CYLINDERS

| Re | P (mm Hg) | $\frac{dm}{d\theta}$ $\left(\frac{g}{sec}\right)$ | Δt (°C) | H_v $\frac{g-cal}{g}$ | k_a $\frac{g-cal}{(sec)(sq\ cm)(°C/cm)}$ | Nu | $\frac{gl}{c^2}$ |
|------|--------------|--|--------------------|----------------------------|---|-------|------------------------|
| (a) | (a) | (a) | (b) | (c) | (c) | (d) | (d) |
| 2120 | 249 | 0.105 | 32 | 592 | 5.94×10^{-5} | 89.0 | 7.77×10^{-12} |
| 2080 | 992 | 0.250 | 20 | 585 | 6.06 | 32.8 | 1.95 |
| 2160 | 765 | 0.317 | 24 | 587 | 6.06 | 34.7 | 2.54 |
| 2250 | 112 | 2.500 | 40 | 597 | 5.88 | 172.5 | 17.30 |
| 2140 | 1700 | 0.133 | 14 | 581 | 6.15 | 24.5 | 1.14 |



^aData by Gilliland and Sherwood (reference 11).

^bData from fig. 9.

^cReference 12.

^dCalculated.

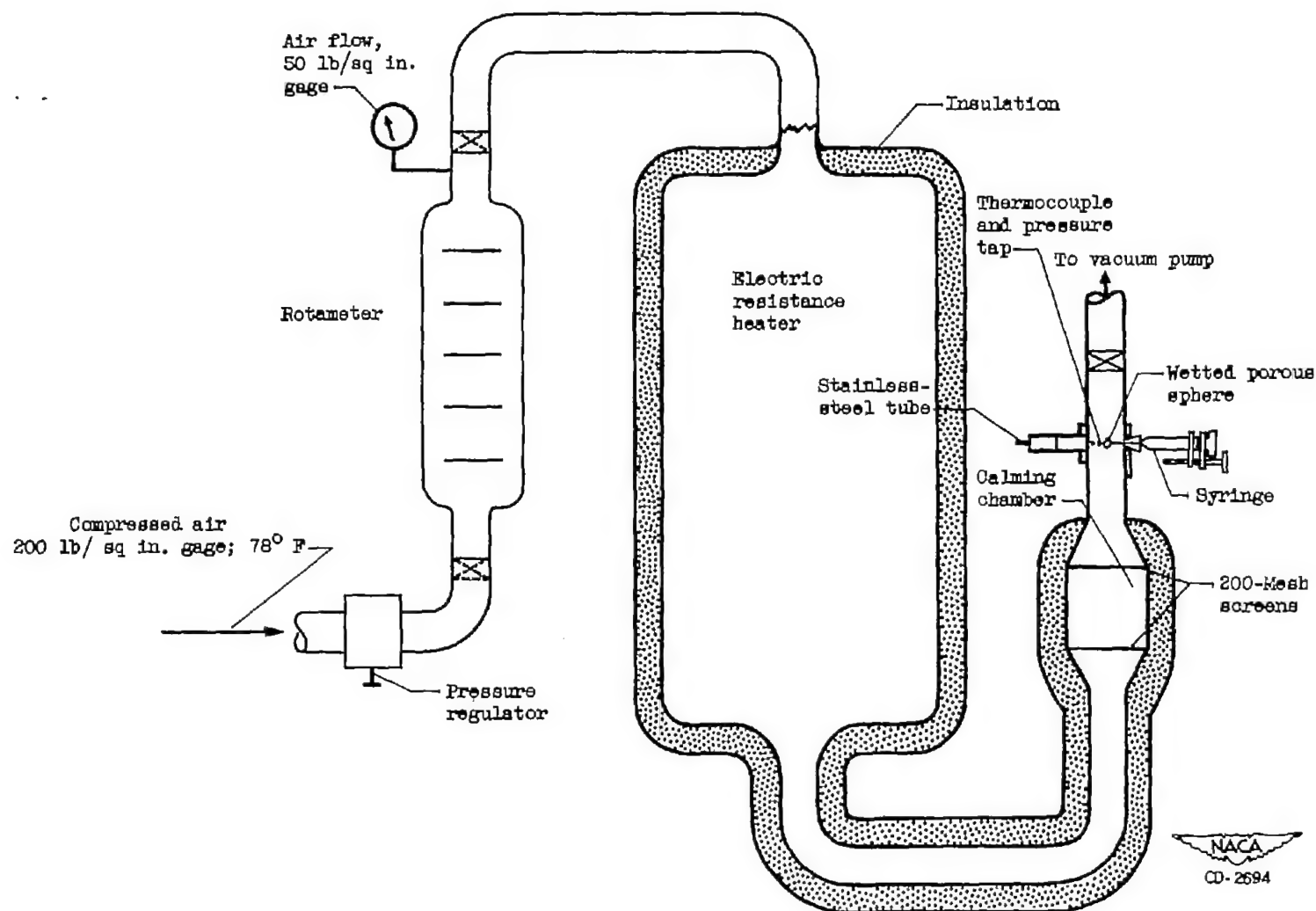
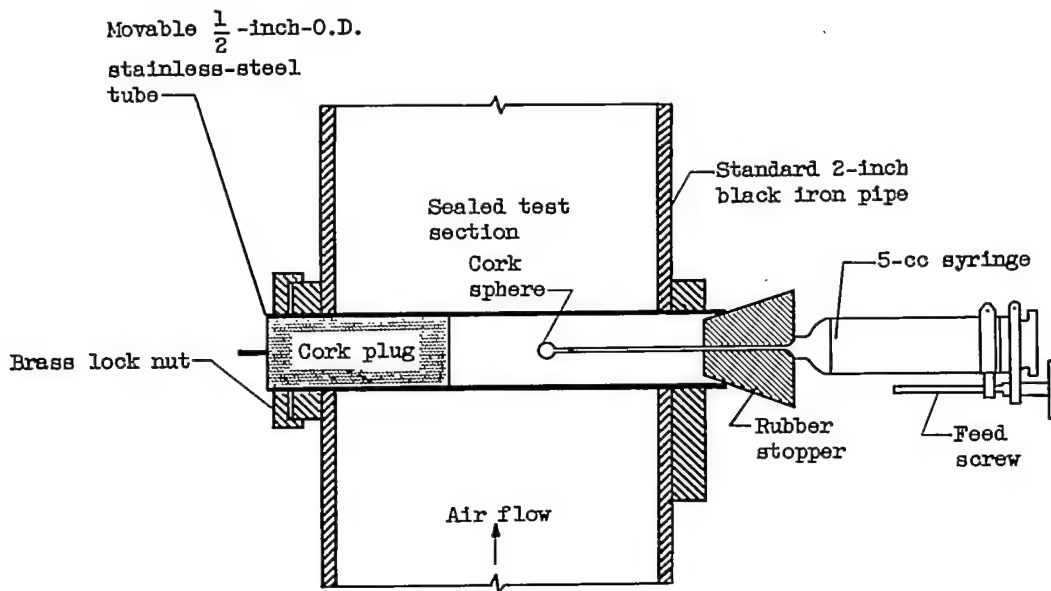
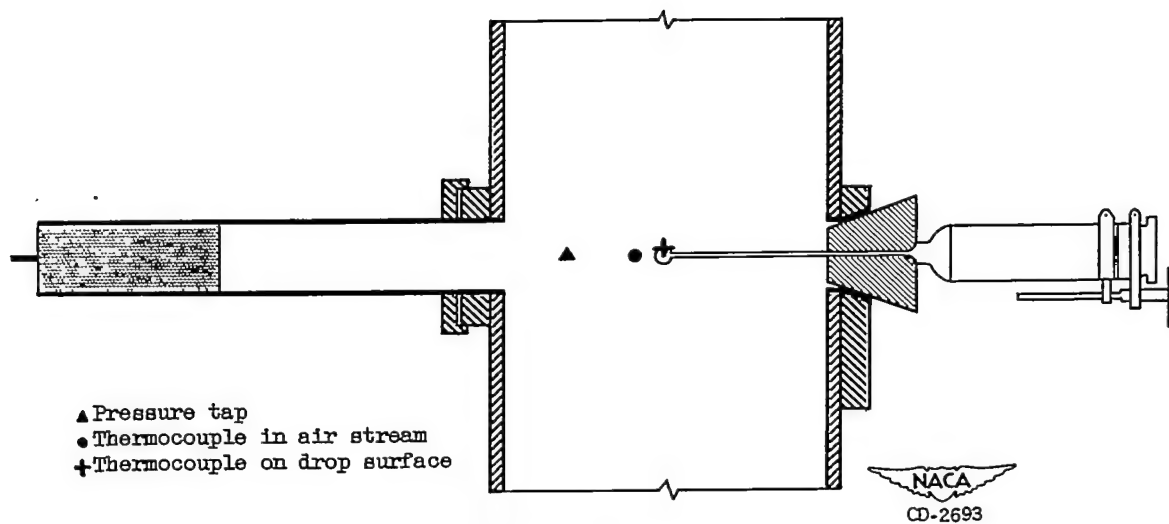


Figure 1. - Schematic diagram of vaporization equipment.



(a) Before and after test.



(b) During tests.

Figure 2. - Vaporization unit.

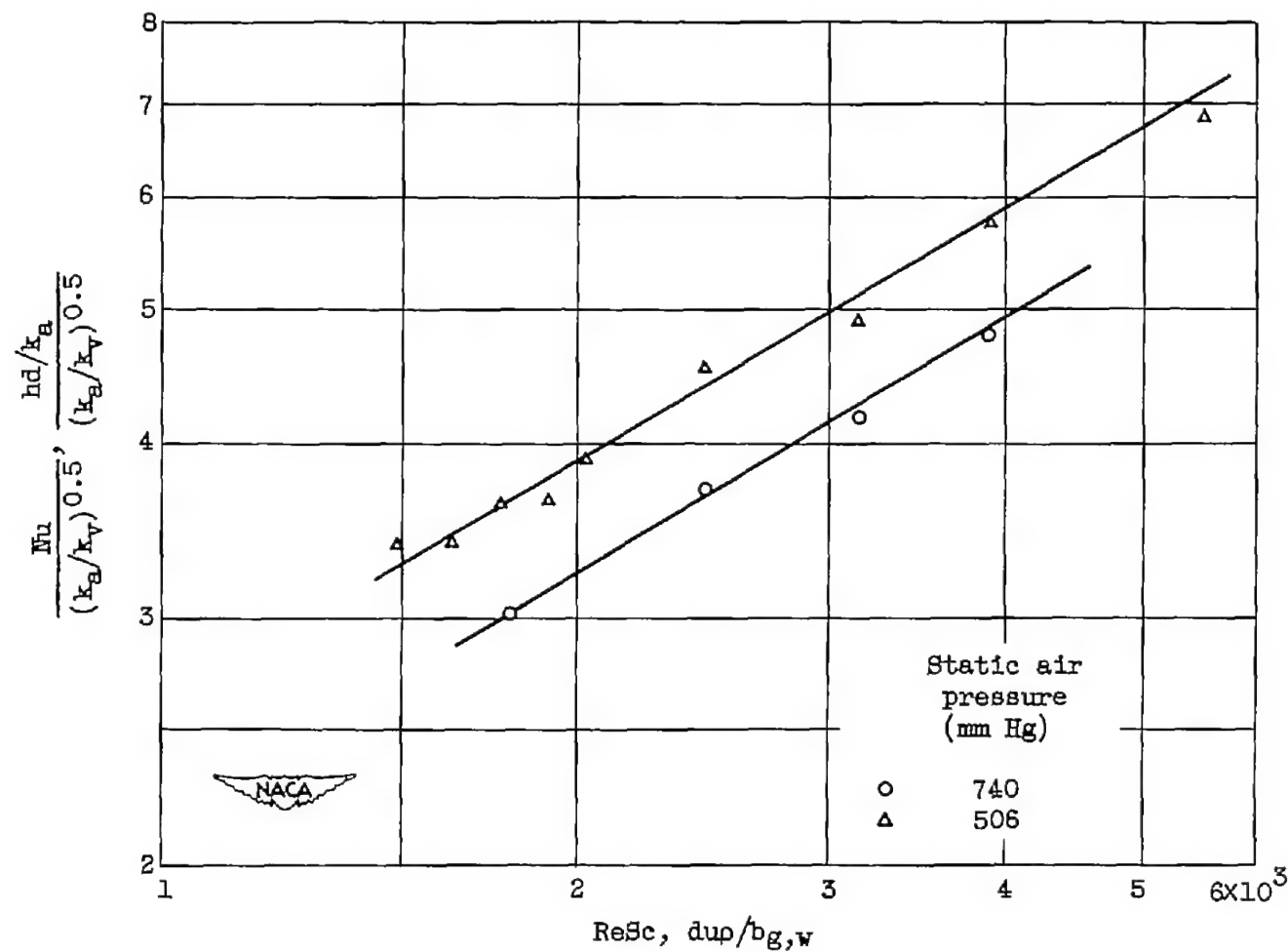


Figure 3. - Vaporization of methanol from 0.71-centimeter-diameter sphere in (28° C) air stream at near atmospheric and reduced pressures, and variable air-mass-flow rate.

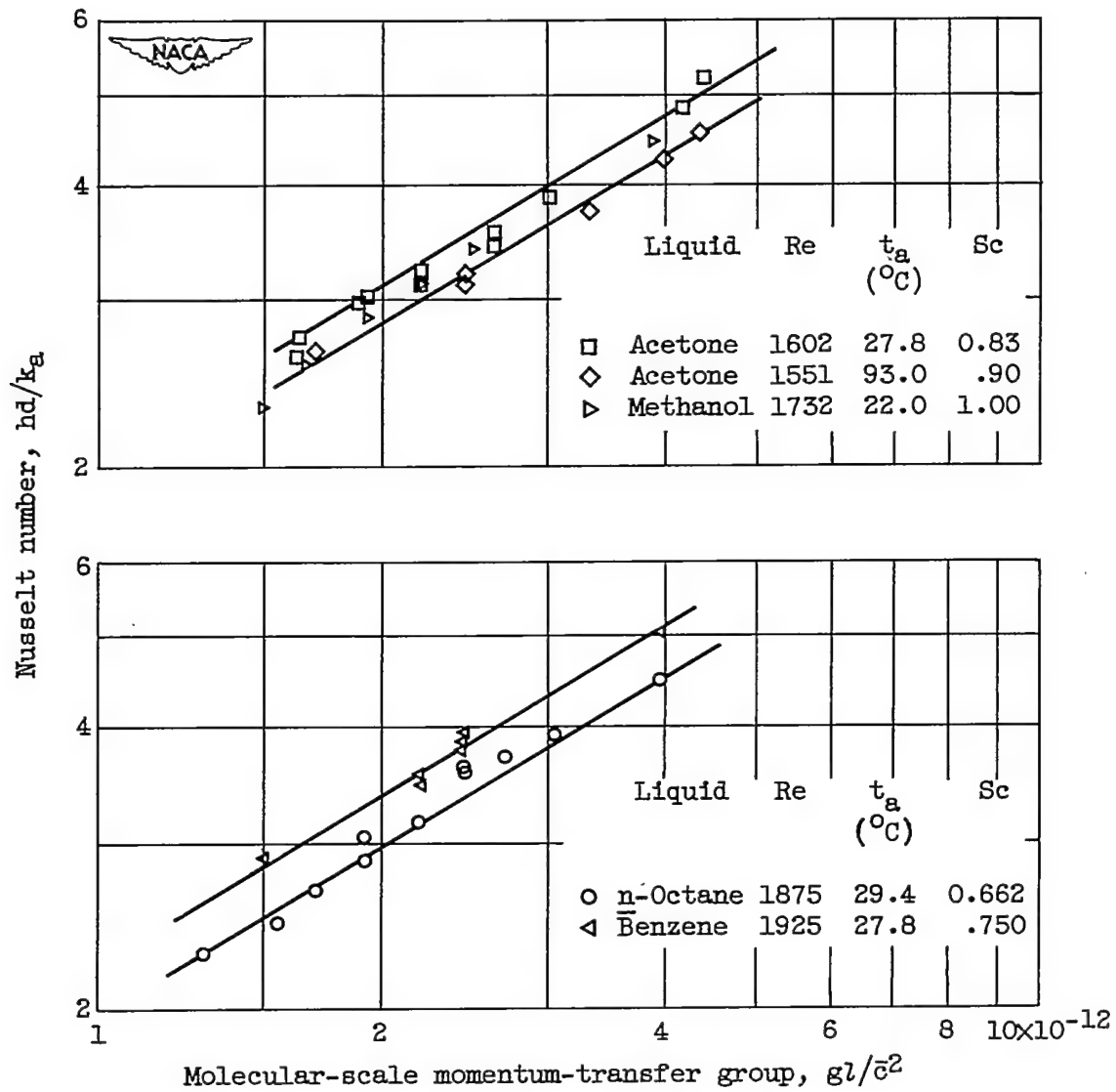


Figure 4. - Correlation of Nusselt number with molecular-scale momentum-transfer group. Air-mass-flow rate, 9.33 grams per second; static pressure, 450 to 1500 millimeters of mercury.

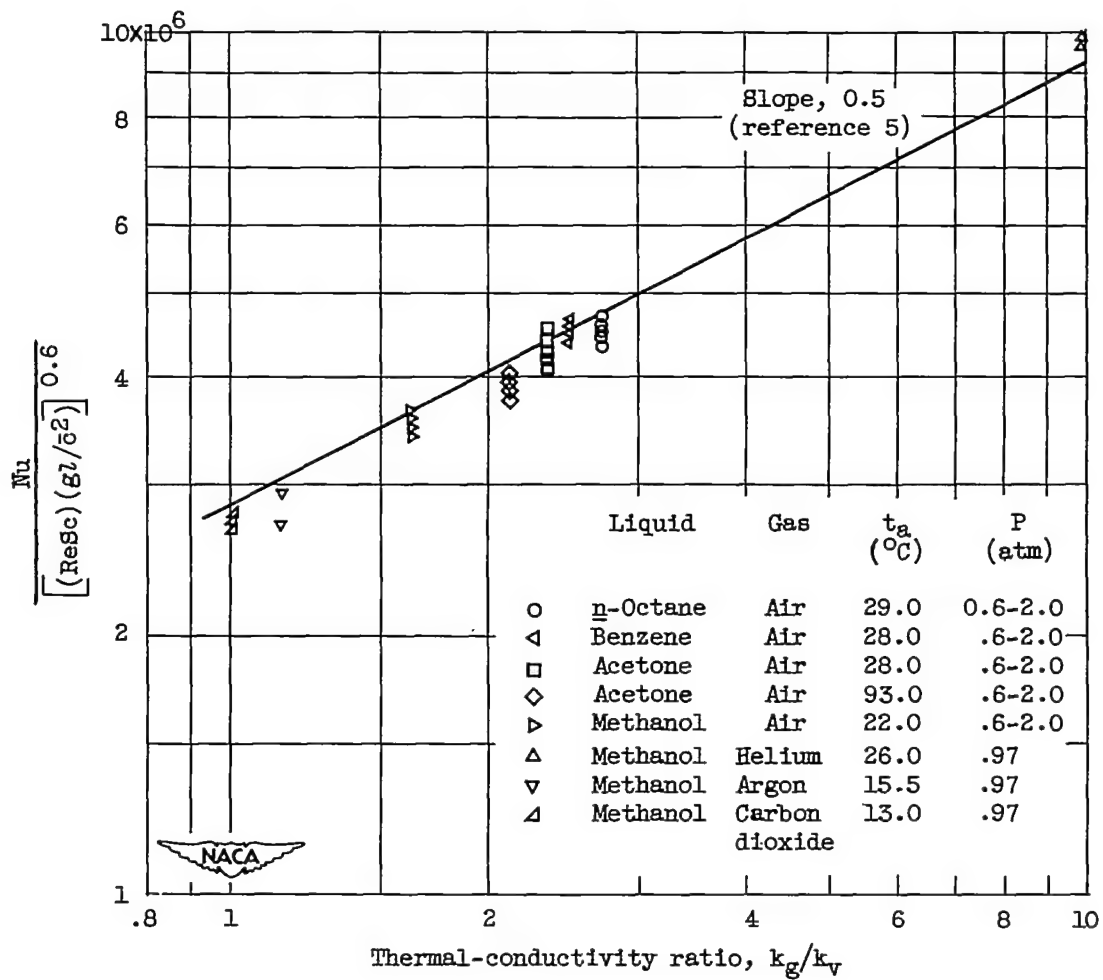


Figure 5. - Correlation of vaporization data with thermal-conductivity ratio.

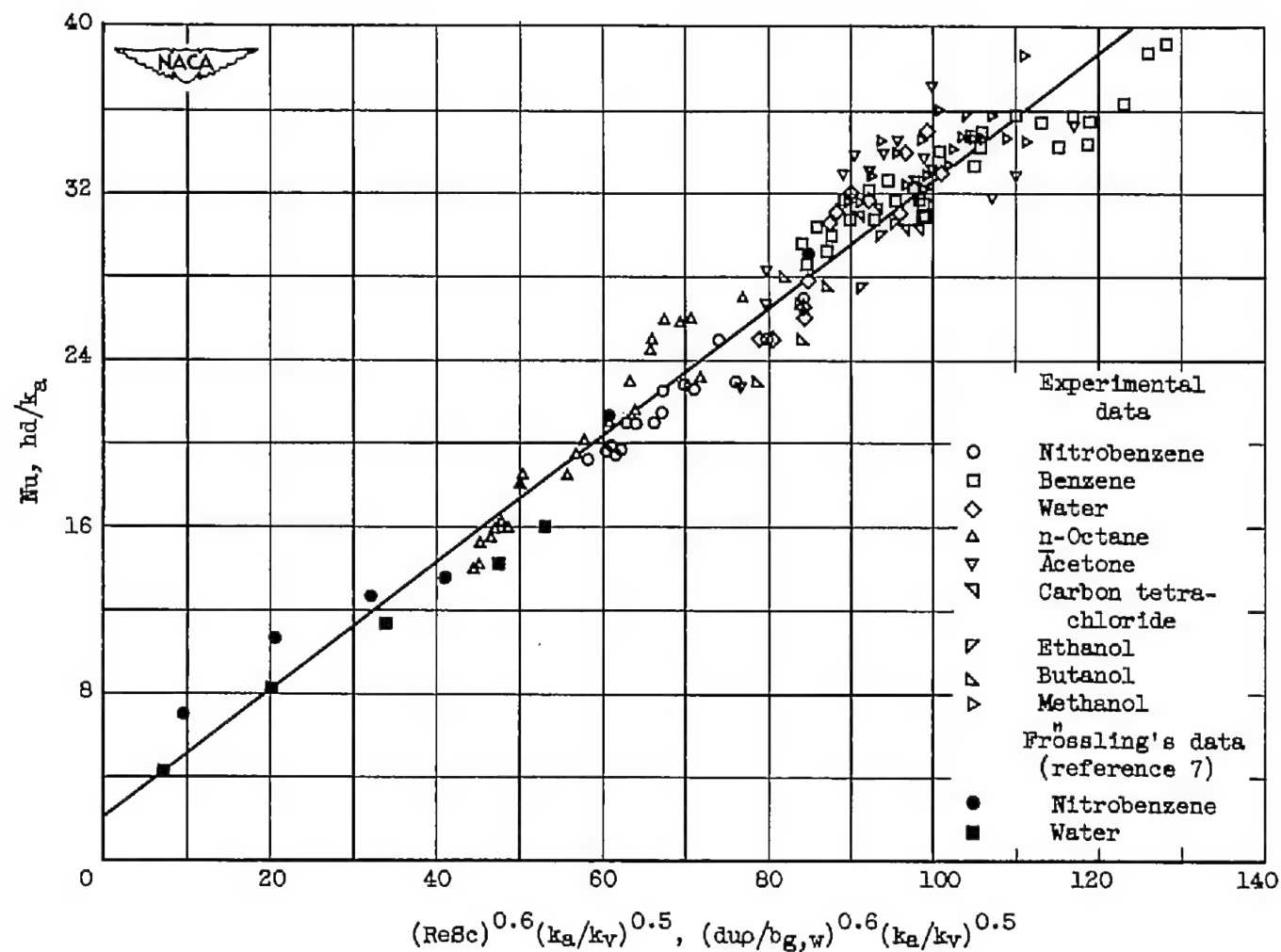


Figure 6. - Correlation of Nusselt number with dimensionless groups $ReSc$ and k_a/k_v .

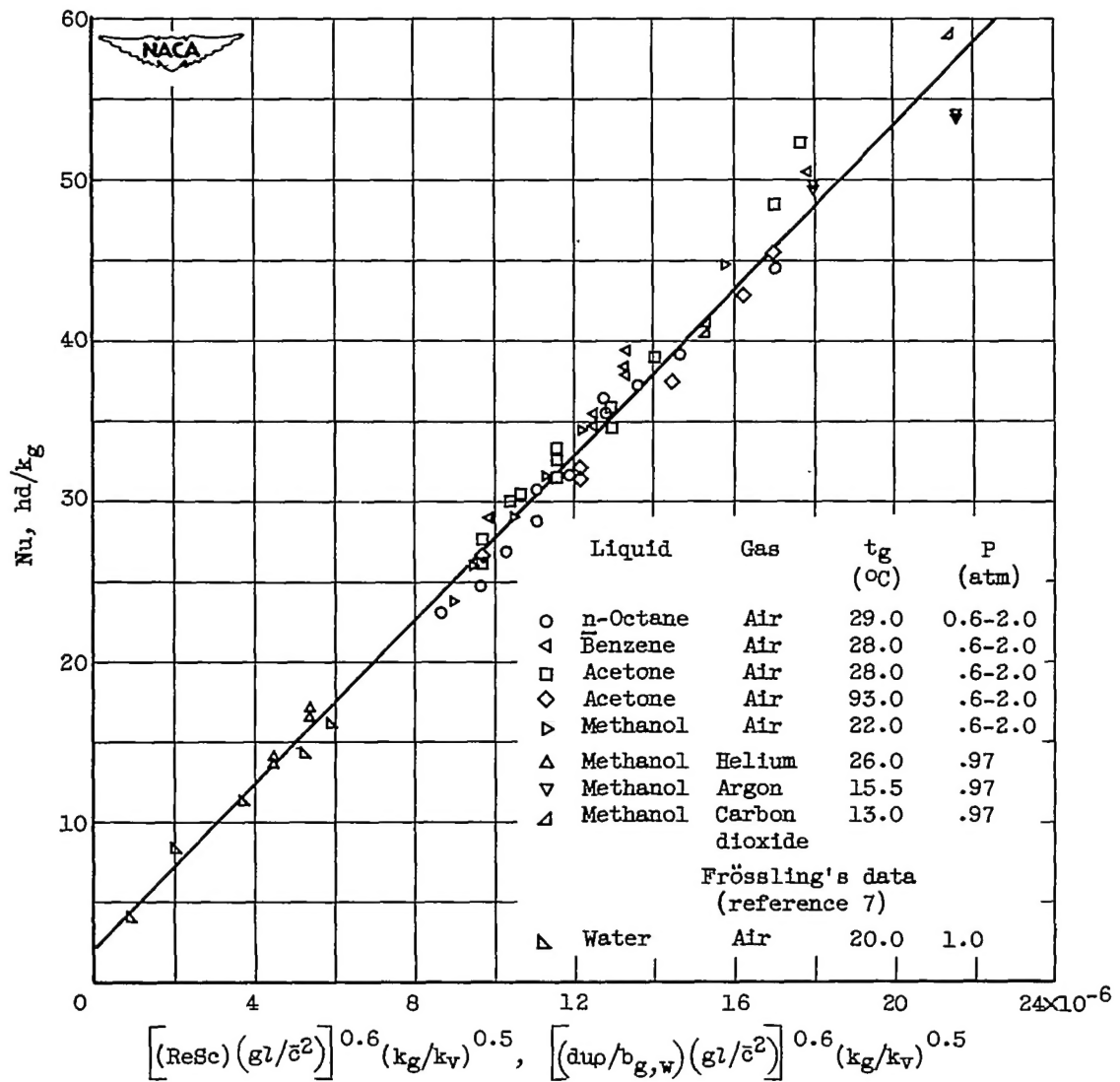


Figure 7. - Correlation of Nusselt number with momentum-transfer groups and thermal-conductivity ratio.

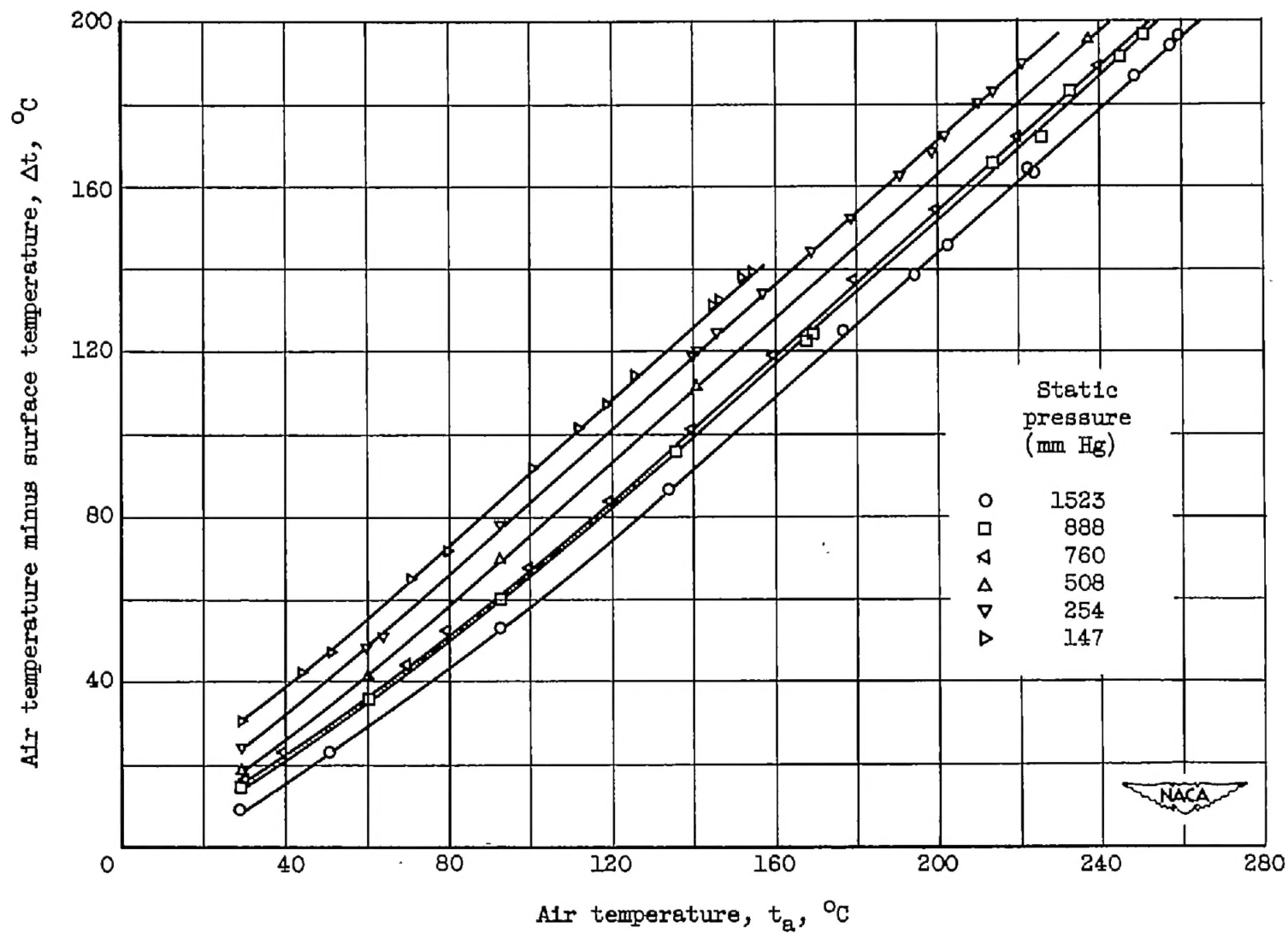


Figure 8. - Psychrometric plot for water at several static pressures.

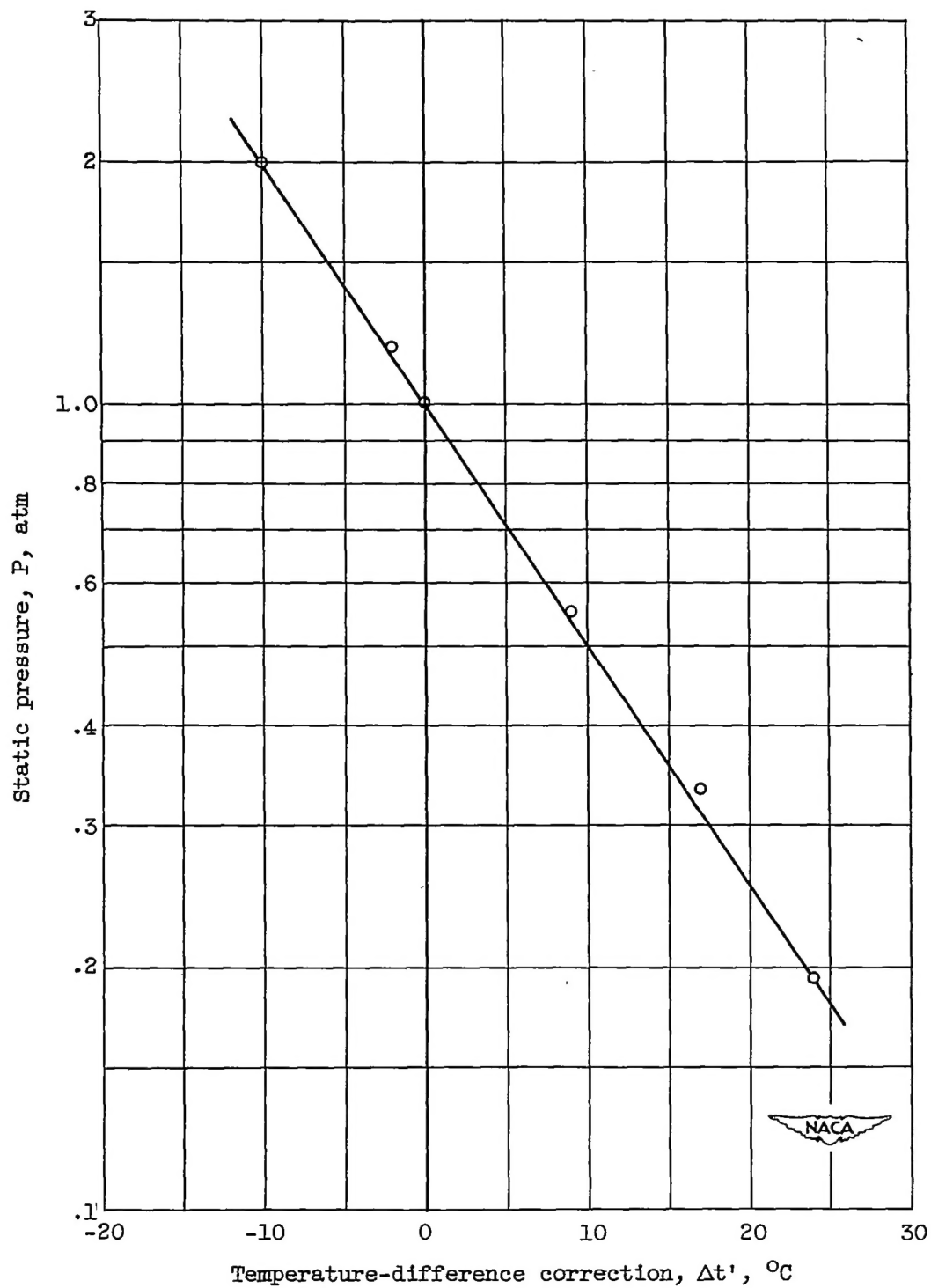


Figure 9. - Correlation of temperature-difference correction with static pressure.

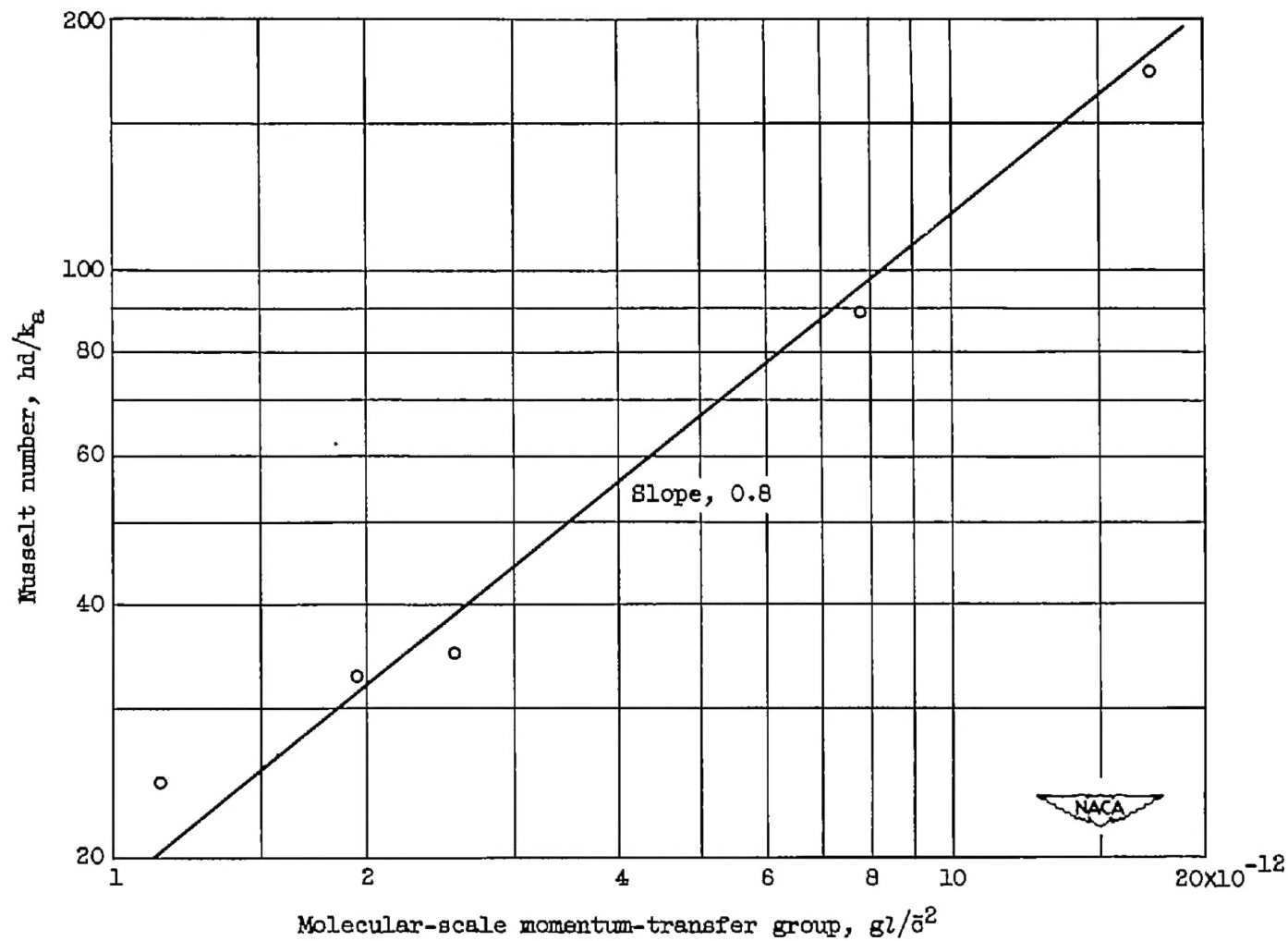


Figure 10. - Correlation of Nusselt number with molecular-scale momentum-transfer group for evaporation inside wetted-wall columns. (Data from reference 9.)